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Walter R. Hearn
Iowa State University

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DR. WALTER R. HEARN
Iowa State University

Growth and Fragmentation of Science

The exponential growth of **science,** with its continuing fragmentation into separate **sciences,** is familiar to all of us. About 1000 specialties appear on the current list published annually by NSF for use with the National Register of Scientific and Technical Personnel. The current (11th) edition of American Men of Science requires six volumes to list 135,000 physical and biological scientists in the U.S. and Canada, a 40 per cent increase over the edition published five years ago; ten years ago one volume each took care of physical, biological, and social scientists—but many biochemists insisted on cross-listing as both physical and as biological scientists. You can see that biochemists have helped to put scientists back together! Maybe the emerging psychobiochemists (or biochemical psychologists—anyway, the people who study the metabolism of LSD along with its other effects) will some day drag the social scientists back in as well. Keeping the nomenclature of new disciplines straight **can** be a problem; I understand there is a significant difference between the fields of microhydrobiogeochemistry and of microbiohydrogeochemistry—but I'm not sure what it is. Two years ago at the annual refresher course of the Iowa Science Teachers Association, I got so into the interdisciplinary spirit that I gave a lecture on "botanical astrophysics"—a branch of science whose subject matter has not yet been demonstrated even to exist!

Hearn

The uneven distribution of people in various sciences depends on factors other than relative newness: in the United States, for example, there are about 100,000 chemists but only about 1000 scientists in all branches of astronomy. Further, only 52 per cent of the world's chemical papers are even published in the English language; in 1965 the next highest percentages were 20% in Russian, 10% in German, 5% in French, and 4% in Japanese. **Chemical Abstracts** published 195,000 abstracts in 1965, bringing their 59-year total to almost three-and-a-half million. About 11,000 journals are now continually monitored for papers by **Chemical Abstracts,** which

Dr. Hearn is assistant professor of chemistry at Iowa State University. He is an especially literate and interesting speaker and writer who can combine the arts and sciences.

classifies chemistry and chemical technology under 74 different headings, by the way.

I am sure most of you share with me not only awareness of this "publication explosion" but also the feeling of frustration it imparts, for as the specialist's knowledge increases, so inevitably does the area of ignorance of the non-specialist—and of the inefficient specialist. If you pride yourself in having a general interest in science, then yesterday you missed about 1000 papers; if you are willing to narrow your interest down to a field such as mine, biochemistry, your ignorance increased by only about 500 papers yesterday—which I confess is not much comfort. In fact, if you are embarrassed to be ignorant, you are in for psychological trouble; the last man who could feel he was keeping up-to-date in the sciences lived about 350 years ago in the latter part of the Renaissance. I gladly pass on to you the one bit of comfort I have found recently, following a stirring challenge by the president of my university to the faculty to create on our campus "nothing less than a new humanism." The vision that came over me of seriously trying to be a "renaissance man" in the 20th century (when I can't keep up even with biochemistry) drove me almost to despair until I discovered in a book on the history of art that Leonardo da Vinci and Michaelangelo Buonarroti, those two Renaissance men **par excellence,** were so burdened down already in the 16th century that both were notorious for not finishing any of their works on time! That cheered me up so much that I kept reading that fascinating book all the way through the Impressionists—and forgot about the 500 biochemistry papers I missed that day.

My subject is "Putting Science Back Together" but you and I both know that in teaching we cannot do that in any simple sense. We cannot cram **all** the proliferation of even a single discipline into a single textbook, or into a single mind—our own or that of hapless students who fall into our clutches. We have to be painfully selective. We may have a lingering nostalgia for "the good old days" when the essence of alchemy could be inscribed on the Smaragdine Tablet of Hermes Trismegistus in thirteen weighty epigrams—and be considered still worth translating 2000 years later; but today's chemical texts are weighed in kilograms, not epigrams, and a new edition lasts two years, not 2000.

Science is not the only thing that grows exponentially, of course. The human population grows that way, and all academic disciplines along with it. More novels and poems are written each year for the English teacher to cope with. New countries crop up before the geographer has learned how to pronounce last year's. There is more history, more theology, more art; Russian and Chinese have to be added by the language department; archeology keeps even the classics alive with new interpretations. It has always been this way—at least since the Renaissance. Whatever it was that Mark Hopkins is supposed to have taught that boy on the other end of the log (or log table, I forget which; it may have been math instead of forestry)—by the time he finished, the kid's ignorance had increased more than his knowledge. There was

more knowledge to be ignorant of!

But I come to bury Mark Hopkins, not to praise him. We are science teachers, and teaching science does pose special problems. In particular, we preside over labs instead of slabs, in which we hope to guide students from their own observations to their own discoveries or at least demonstrations of significant relationships between observable facts. The essence of science is generalization, and generalization eventually means simplification. Herein lies our only real hope of "putting science back together." In a sense it keeps putting itself back together, but in patterns that keep breaking through established boundaries of narrow specialization. Encompassing principles, such as evolution or quantum mechanics; common techniques, such as spectrophotometry or the use of isotopes; interdisciplinary programs, such as the IGY or the moon shot—all contribute to a spirit of unity still detectable in science.

However, the point I wish to make today is that school teachers have perhaps a greater opportunity than others, and hence a particular obligation, to do something intentional to put science back together. In the first place, the students you teach are less likely to be already committed to specialization than college students. In the second place, you yourselves can

CONSTITUTION OF THE IOWA SCIENCE TEACHERS SECTION

Article IV. Officers

Section 1. The elected officers of this section shall consist of a President, a Vice-President, a Secretary, and a Treasurer.

Section 2. The Executive Committee of the section shall consist of the four elected officers in addition to the immediate past-president, one regional director (to be selected by the other regional directors at their fall meeting), and the Journal Editor (ex-officio).

Section 3. The Board of Directors of the section shall consist of the members of the Executive Committee as well as the nine regional directors who will be appointed each year by the Executive Committee to represent the members in the particular region.

Section 4. Any active member of the section is eligible to hold any office with the exception of the presidency. The two nominees for the office of president must have served on the Executive Committee prior to nomination for office.

Section 5. The election of officers shall be held before the fall meeting of the section with a vote by mail. A majority of affirmative votes of those members returning marked ballots shall be necessary for election to any office.

Section 6. The term for each office shall be for one year. A duly elected officer shall serve until his successor is elected and assumes office unless he reigns or is voted out of office by two-thirds of all members of the Board of Directors.

Section 7. A simple majority of the membership of the Executive Committee shall constitute a quorum for the transaction of business.

Section 8. All vacancies in the offices of this section when not specifically provided for in this Constitution shall be filled temporarily by appointment by the Executive Committee. Such duly appointed officers shall hold office until the close of the fall meeting when new officers are ordinarily elected or appointed.

still afford to be generalists; indeed, many of you in the smaller schools are probably forced to be!

Putting Science Back Together—Laterally

I see several different dimensions in which you could help to put science back together. The most obvious is that of breadth, the interdisciplinary or "lateral" dimension already alluded to. Whatever you teach, and however you teach it, let me urge you to make your teaching of science as broad and rich as possible. As a professional biochemist, I hesitate to say anything at all about how to teach to a group of professional teachers, but perhaps you may grant that at least I might know something about how to learn. At any rate, my impression is that there are basically three different ways to go about teaching: (1) the **logical** approach, in which you start with the final framework of knowledge and work backwards; (2) the **chronological** approach, in which you start at the historical beginning and work forwards; and (3) the **phenomenological** approach, in which you start where the student is and go with him whichever way he goes. I suspect that many of us would pay lip service to the latter as being most effective, but in practice we seldom make use of it because it is the least efficient approach. It is too risky, **too** interdisciplinary. Who knows what a student may ask if we give free reign to his curiosity? Besides, each student starts at a **different** place and with a class of more than one chaos is already upon us; Mark Hopkins had a snap, even if he had problems with elm beetles running up his pant legs!

Many of us also see value in teaching a subject from a chronological or historical point of view, and a scientific subject taught this way would almost automatically tend to be interdisciplinary. Science **grew,** with fissions and fusions between various channels of thought that would be obvious if we let students re-live the development of any branch of science. However, most of us shy away from wholeheartedly teaching this way, although we may sprinkle our courses with historical anecdotes for flavoring. We are probably afraid that even abbreviated history would take too long to repeat itself—and "it's the modern stuff that the kids really need to know." Further, historically oriented textbooks are rare —and so are historically oriented science teachers, and scientists.

In practice, most of us teach a subject in a logical fashion, or at least in as logical a fashion as our equipment allows us to. This method keeps the students at a respectable distance from the teacher and thus helps to maintain discipline. The master knows what is going on; the novices do not. The first principle is cast like a pearl before them—if they respond appropriately the master (who may be a machine) rewards them by going on to the next step. There is never any risk, any doubt about who is in command. The only doubts are in the minds of the more imaginative students, doubts about whether it is worth going through all this. I am not here today to debate pros and cons of various pedagogical postures: there are **many** ways to teach. I might point out, however, that even in science courses based largely on open-ended experimentation by students, the **sequence** of experiments, the **pattern** of the course, the **logical structure** of the

subject is generally set by the teacher. We have the **experiments** open-ended so the student can grasp relationships for himself—but we structure the **course** for him, to avoid confusion.

The point I do want to make here is that a certain amount of confusion is an important aspect of modern science, and that there is no single logical structure for science as a whole or for any of the sciences in particular. The early reductionist models of the structure of science are simply no good any more. That pyramid in which biology was being reduced to a branch of chemistry, chemistry to physics, and physics to a few basic mathematical equations—well, that was an inverted pyramid and it was bound to topple. What we have now is more like a sphere with the various sciences staked out on its surface, and you can roll the sphere around any way you want and make the whole thing rest on **your** branch of science. That's the way the sphere bounces, and young people should be made aware that no science is logically more basic than any other science. You cannot put science back together today by stacking the other sciences in the "proper" order on top of physics. A goose named physics may have laid all the golden eggs a few years ago, but have you taken a gander at modern biology? What was good for that goose has now set the gander up in business: just as biological behavior was thought to be "explained" on the basis of physical phenomena, human behavior was realized to be "explainable" on a biological basis—and what behavior is more characteristic of humans than the development of abstractions such as physics and mathematics? Hence, physics is as much a specialized branch of biology as biology is a specialized branch of physics.

It is true that a cyclic model of the structure of science is not fully appreciated or welcomed by scientists. A bipolar model, even a horizontal one, is simpler and less disturbing to our hubris. With the sciences polarized toward the simplicity of physics and math at one end and toward the complexity of biology (and the gosh-awful mess of the social sciences) at the other end, a scientist could find a cozy niche surrounded only by his fellows of nearly identical polarity. Reading the same scientific paper, some of us study only the equations

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CONSTITUTION OF THE IOWA SCIENCE TEACHERS SECTION
Article V. Duties of the Officers

Section 1. The President

The president shall preside at all meetings of the section, all meetings of the Executive Committee, and all meetings of the Board of Directors.

He shall notify each member of the time and place of all such meetings.

He shall represent the association wherein possible at other state, regional, and national meetings.

He shall appoint the chairman and members of all committees with the advice and consent of the Executive Committee.

He shall be an active worker on the spring Meeting Committee and the chairman of the Policy and Resolution Committee.

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and skip the paragraphs in between explaining them in words, and some read only the paragraphs, not even focusing on the mathematical symbols; a few enjoy both. This situation is not likely to change; what should hopefully begin to fade is a feeling of either pride or humility over being one way or the other. There is more than one way to do science. Someone has said that doing physics today is like climbing a mountain but doing psychology is like exploring a jungle. The eminent professor of the history of science at Oxford, Alistair C. Crombie, has pointed out what a tremendous advance it was in 1604 for Kepler to reduce the human eye to a simple camera-like mechanism—but also that this simplification which took such intellectual efforts to discover raises the least interesting problems in the study of vision!

The dynamic tension between simplicity and complexity we see in science as a whole is also exemplified in each of the sciences, and this is just what I am urging you to put across to your students—or to let them discover by themselves, if that is your style of teaching. Show that whatever science you are teaching **is** actually an interdisciplinary subject (i.e., it lies between other disciplines), that it moves simultaneously toward **both** simplicity and complexity—in short, that it is **alive.** Let your students **live** it if possible, but at least show them that it is alive and in living interaction with other branches of science. Let your biology overlap with chemistry at one end and with human ecology at the other—the two are not nearly so far apart as they used to be. Let chemistry explore what it can of both quantum mechanics and metab-

olism to demonstrate both the basis and the application of chemical principles. And physics—what of physics? At which end of physics is it most alive—at the imperfect crystallinity of DNA which seems to drive physicists into philosophy, or at the substructure of the nucleus, where a "menagerie" of strange particles keeps popping out, driving physicists to higher and higher energies to get to the bottom of the quirks in their quarks? And mathematics—has all the life been squeezed out of it? Hardly, with biologists on the staff of IBM to assist in computer design—or when statistical grappling with biological and social complexity is considered part of mathematics. And what is going on in astronomy, that coldest and most distant of the natural sciences? What will be found in that moon dust? And what are those "quasi-stellars" with either their incredible sizes or their incredible distances? Clearly there is life in the space sciences whether or not there is life in outer space!

The problem for us as teachers is to recognize the **life** in science and introduce it in our classes. I realize that this is not easy; life in its fullness is always complicated and therefore unpredictable and difficult. A museum is easier to manage than a zoo! And there is the serious danger of dilution if we bring in too much that is peripheral; safer to stay "on dead center"! Broaden a course, or a stream, you will say, and it gets shallow. Of course, there are rivers that are both broad **and** deep, and trickles that are narrow **and** shallow—and the latter are the ones that are most liable to go dry.

Putting Science Back Together—Longitudinally

Having said all I dare about giving breath—and breadth—to your courses, I want to stress your role in another dimension, the "longitudinal" one. I think that is the term used in psychology for studies carried out over the life-span of a child. Here again, however, a cyclic or helical model may be more appropriate than a linear one. That is, instead of placing elementary education at the obvious beginning and graduate school at the obvious end-all, we should also remember that in "higher" education we prepare people, be they teachers or potential parents, to start the cycle around again. I think science education has come apart, however, in this dimension, those who teach at one point on the continuum seldom understanding what goes on at other loci, although we have all looped the loop at least once ourselves.

(continued next issue)

CONSTITUTION OF THE IOWA SCIENCE TEACHERS SECTION

Section 2. The Past President

The immediate past president shall be a part of all meetings of the Executive Committee and the Board of Directors.

He shall serve as an ex-officio member of the Election Committee.

He shall serve as chairman of the Spring Meeting Committee.

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